

INTERPLANETARY MAGNETIC FLUX DEPLETION DURING PROTRACTED SOLAR MINIMA

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Received 2010 March 29; accepted 2010 November 13; published 2010 December 22

ABSTRACT

We examine near-Earth solar wind observations as assembled within the Omni data set over the past 15 years that constitute the latest solar cycle. We show that the interplanetary magnetic field continues to be depleted at low latitudes throughout the protracted solar minimum reaching levels below previously predicted minima. We obtain a rate of flux removal resulting in magnetic field reduction by 0.5 nT yr^{-1} at 1 AU when averaged over the years 2005–2009 that reduces to 0.3 nT yr^{-1} for 2007–2009. We show that the flux removal operates on field lines that follow the nominal Parker spiral orientation predicted for open field lines and are largely unassociated with recent ejecta. We argue that the field line reduction can only be accomplished by ongoing reconnection of nominally open field lines or very old closed field lines and we contend that these two interpretations are observationally equivalent and indistinguishable.

Key words: interplanetary medium – magnetic fields – solar wind

Online-only material: color figure

1. INTRODUCTION

Recent studies of the current solar minimum have shown a significant reduction in wind speed and solar wind density (McComas et al. 2008) relative to past solar minima along with a record reduction in the interplanetary magnetic field (IMF) intensity and flux (Smith & Balogh 2008; Connick et al. 2009). Although the record low solar wind density and speed are of significant interest and raise many important questions about the source and acceleration dynamics of the solar wind, we contend that the record low IMF is largely unrelated and can be understood only in terms of one ongoing dynamic: the removal of magnetic flux via reconnection below the Alfvén critical point. Other factors may play into the actual rate of reconnection and flux removal, but only reconnection can accomplish the reduction of the IMF.

At least two recent papers argue there is a minimum to the IMF intensity (Fisk & Zhou 2008; Owens et al. 2008). The arguments behind these minima are based largely on solar physics arguments and the movement of field lines within the photosphere. In contrast, Lockwood et al. (2009) argue the absence of an IMF minimum. We see no evidence to date of a minimum with every indication pointing to a quasi-steady loss of magnetic field due to the ongoing reconnection of field lines that continues throughout the protracted solar minimum. Our companion paper (Schwadron et al. 2010) performs a re-interpretation of the Owens et al. (2008) paper using rates inferred here and computes a new minimum for IMF intensity that is well below previous estimates and well below the measured flux at the end of 2009. This new minimum is based solely on the balance between ongoing magnetic reconnection and the slow, but steady input of flux by CMEs during the protracted and generally quiet solar minimum.

Bieber & Rust (1995) derived expressions that attempt to separate the flux of open field lines from contributions due to the azimuthal or toroidal fields that represent departures from the Parker (1958, 1963) prediction for the IMF spiral. Contributions to the toroidal field component were shown by Smith & Phillips (1997) to reside almost exclusively within

and around interplanetary manifestations of CMEs (ICMEs). Connick et al. (2009) applied this formalism to the last decade of 1 AU and *Ulysses* observations in an effort to extend the results of Bieber & Rust (1995) into the current solar cycle and include high-latitude observations by the *Ulysses* spacecraft. They found that the last solar cycle closely resembled the measurements of past cycles at low latitude, but that there was evidence of very little toroidal flux injection at high latitude. Here, we use the computed flux of toroidal fields as an independent proxy for ICME activity and the potentially larger question of flux injection. We use the computed flux of open field lines to demonstrate that the ongoing IMF reduction is accomplished by removal of open field lines.

In the following analysis, we show first that the intensity of the IMF at 1 AU and the flux of field lines crossing a 1 AU Gaussian sphere continue to decline throughout the recent solar minimum. We show that the rate of decline of the IMF intensity at 1 AU over the solar minimum years 2007–2009 is $\sim 0.3 \text{ nT yr}^{-1}$ while in previous years the decline was greater and argue that only magnetic reconnection below the Alfvén critical point can achieve this reduction. We then associate the rise in IMF intensity during the rising phase of the solar cycle with the injection of toroidal flux either by ICMEs or any other form of rising loop structure such as is predicted by the Potential Field Source Surface (PFSS) model. We recognize that reconnection rates may increase during the rising phase of the solar cycle when new flux is injected into the heliosphere, but we argue that a quiet Sun exhibits a nearly steady reconnection of magnetic field lines below the Alfvén critical point leading to a depletion of the IMF during solar minimum years. We recognize that solar processes during a protracted solar minimum may act to keep fields of opposite polarities apart and that these processes may eventually limit the decline in IMF intensity.

2. ANALYSIS

We have analyzed Omni data (King & Papitashvili 2005) from 1963 through day 331 of 2009 and computed IMF average intensities and fluxes for each sector type (toward and away)

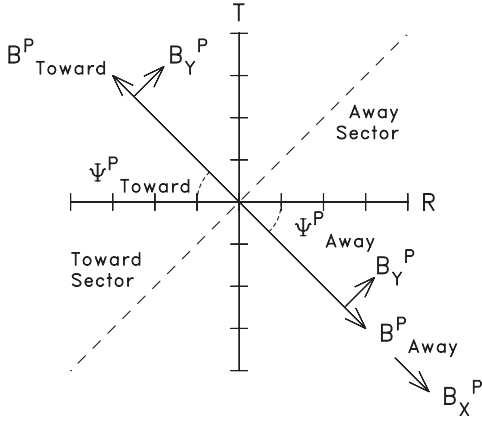


Figure 1. Definitions of B_X^P and B_Y^P relative to the spiral direction.

with grand averages computed across the heliospheric current sheet (HCS). We refer the reader to Connick et al. (2009) for a discussion of previous solar cycles. Here, we focus on the most recent and ongoing solar minimum and preceding maximum.

Figure 1 shows the variables B_X^P and B_Y^P defined by Bieber & Rust (1995) in their study of toroidal field injection by ICMEs. In their analysis they project the measured IMF onto these two new rectilinear coordinates that are oriented relative to the expected Parker spiral direction according to

$$B_X^P = B_R \cos(\Psi^P) - B_T \sin(\Psi^P) \quad (1)$$

$$B_Y^P = B_R \sin(\Psi^P) + B_T \cos(\Psi^P), \quad (2)$$

where B_R (B_T) is the IMF coordinate in the radial (tangential) direction. The radial direction is defined to be the vector from the center of the Sun to the spacecraft location. The tangential direction is defined to be coplanar with the Sun's rotational equator and directed in the sense of the Sun's rotation. Ψ^P defines the spiral angle between the IMF and the radial direction in the R - T plane (Parker 1958, 1963)

$$\tan(\Psi^P) \equiv \frac{2\pi R \sin(\Theta)}{V_R T} \left[1 - \frac{b}{R} \right], \quad (3)$$

where $\Theta \simeq 90^\circ$ defines the co-latitude angle for near-Earth measurements, V_R is the radial component of the solar wind velocity, $T = 25.4$ days is the sidereal rotation period of the Sun, $b = 5 R_S$ is a nominal source radius for the solar wind and $R = 1$ AU is the heliocentric distance. The prediction is only weakly dependent on b . For a typical wind speed of 450 km s^{-1} the winding angle $\Psi^P \simeq 45^\circ$. In this formalism, B_X^P represents the projection of the IMF onto the theoretical Parker spiral direction that would be adhered to by open field lines excluding instances such as draping or the radial fields sometimes seen in rarefaction intervals (Gosling & Skoug 2002; Schwadron 2002). Likewise, B_Y^P represents field components that are orthogonal to the nominal spiral direction that would be seen within ejecta, behind some shocks, in regions of field line draping, etc.

From B_X^P and B_Y^P we can define incremental fluxes

$$\delta\phi_{\text{open}} = B_X^P \cos(\Psi^P) \quad (4)$$

$$\delta\phi_{\text{toroid}} = V_{\text{SW}} B_Y^P \cos(\Psi^P) \quad (5)$$

that can then be integrated to yield total or average net fluxes. Averages across the HCS require that the sign for open and

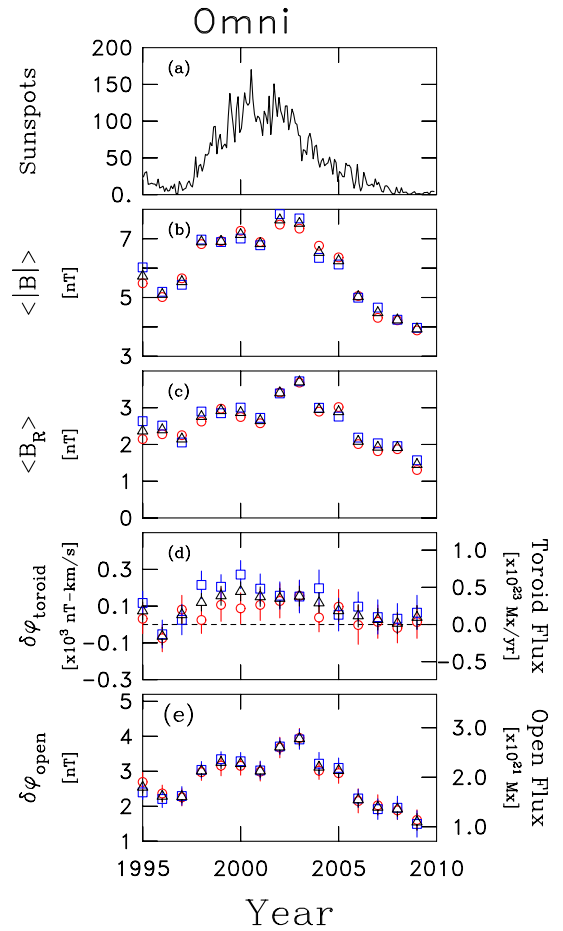


Figure 2. (a) Monthly sunspot number (unsmoothed) spanning the years 1995–2009. In the remaining panels, the color convention is red circles (toward), blue squares (away), and black triangles (average) quantities with sign changes on the toward sector measurements as described in the text. (b) Average IMF intensity. (c) Average radial component of the IMF. (d) Incremental and integrated yearly average of toroidal flux. (e) Incremental and integrated yearly average of open flux.

(A color version of this figure is available in the online journal.)

toroidal fluxes change for toward sector measurements in order to avoid simple cancellation. We adopt this convention for incremental fluxes and field components to facilitate comparison. Smith & Phillips (1997) show that the net integrated $\delta\phi_{\text{toroid}}$ is contained within ICMEs and their surrounding fields.

Figure 2 shows the result of our analysis of Omni hourly data. See Connick et al. (2009) for a comparison with earlier solar cycles. Figure 2(a) shows the sunspot cycle for years 1995–2009 and the extended solar minimum. The extreme low values of sunspots for years 2007–2009 are especially evident. Low sunspot number is generally consistent with a low rate of CME ejection, which means a reduced rate of new flux injection into the heliosphere. Owens et al. (2008) show the rate of CME activity falls by a factor of $\sim 8\times$ over the years 2002–2008. They predict a rate of flux injection into the heliosphere by CMEs during solar minimum years that is probably high given that they use estimates for flux contained by an average CME that are derived from solar maximum observations when CMEs tend to be larger. Vourlidis et al. (2010) note that from 2003.5 onward the mass injected into interplanetary space by CMEs as integrated over solar rotations decreases until it is $\sim 50\times$ less than its solar maximum peak at from 2000 to 2003. If mass is a useful proxy for magnetic flux, as would be the case if

the source material were consistently similar, then times of low solar activity display greatly reduced magnetic flux injection by CMEs. However, any analysis of net injection by CMEs is complicated by observation issues at the small scales (Yashiro et al. 2008; Schrijver 2009; Forbes 2010). The remainder of the figure shows computed flux for toward sectors (red circles), away sectors (blue squares), and their average (black triangles). In order to make all quantities visible, we perform yearly averages of the data. Uncertainties are present in the plot, but are generally smaller than the symbols used.

Figure 2(b) shows the buildup of IMF intensity $|B|$ averaged over a year for each sector polarity as well as a grand average across the HCS. Note the rise and fall with solar activity. ICMEs and any other eruptive processes that bring field loops above the Alfvén critical point, as partially represented by proxy through the sunspot number, are responsible for injecting additional magnetic field lines into the heliosphere that must be removed via reconnection at some place and time in order to prevent the continued buildup of magnetic field in interplanetary space. Figure 2(c) shows the increase in the radial component of the IMF with rising solar activity. This leads to a net increase in magnetic flux, but does not address the question of whether that flux is open or closed.

Field lines associated with the limbs of ICMEs leading back from the leading ejecta to the solar foot points are expected to closely follow the Parker spiral even though they are nominally closed field lines if they have not undergone reconnection. A close examination of electron heat flux can determine whether these lines are magnetically connected to the Sun on both ends at least for some period of time until ICME expansion and propagation into the outer heliosphere renders such a test questionable. The value of the Bieber & Rust (1995) formalism is that it allows us to measure the input of field lines into interplanetary space via ICMEs based on long-term averages without dissection of individual ICMEs. Figure 2(d) shows the computed yearly average of toroidal flux due to systematic IMF measurements with projections perpendicular to the Parker spiral direction. As noted by Bieber & Rust (1995) and Connick et al. (2009) this quantity rises and falls with solar activity. This suggests an association between ICMEs and deviations from the spiral IMF while Smith & Phillips (1997) show that $\delta\phi_{\text{toroid}}$ is confined largely to ICMEs as postulated by Bieber & Rust (1995). The systematic non-zero average values of toroidal flux during the rising phase of the solar cycle represent the injection of magnetic field lines in the form of loops either in ICMEs or other erupting loop structures. The abrupt decrease of toroidal flux in 2005 to values within 1σ of zero marks the beginning of the solar minimum years as defined by ICME activity.

Figure 2(e) shows that at the same time there is a rise in IMF intensity associated with the radial component that can be attributed to the flux of “open” field lines, although it is clear that some of these measurements are probably closed field lines that are closely aligned with the Parker spiral direction. Therefore, we must be careful that ϕ_{open} may contain a significant fraction of nominally closed field lines that follow the Parker spiral. At what point is this distinction significant and can we differentiate between a field line aligned with the Parker spiral that originates with ejecta that passed 1 AU 20–40 days ago? At some point and for all practical purposes in this analysis such observations of older ICME field lines will be seen as open field lines in this analysis.

Smith & Balogh (2008) argue that the IMF intensity reached an all-time measured low by 2008. While this is not true of ϕ_{open}

Table 1
Solar Minimum Parameters

Stat	1963–1965	2006–2009
$\langle B \rangle_{\text{min}}$ (nT)	5.06 ± 0.04	3.93 ± 0.02
$\langle B_R \rangle_{\text{min}}$ (nT)	2.12 ± 0.04	1.45 ± 0.02
$\langle \delta\phi_{\text{open}} \rangle_{\text{min}}$ (nT)	1.84 ± 0.14	1.55 ± 0.24
$\langle \delta\phi_{\text{toroid}} \rangle$ (nT km s ⁻¹)	30.0 ± 30.0	39.0 ± 27.0

it is true of $\langle |B| \rangle$ and $\langle B_R \rangle$. Nevertheless, Connick et al. (2009) observed that the 2008 levels (given the data available at the time) were comparable and statistically equivalent to those of 1963–1965. Year 2009 shows still lower flux levels, the lowest ever recorded in the space age including measurements of ϕ_{open} . See Table 1 for a comparison.

2.1. Solar Cycle Dynamics

Comparing photospheric and solar wind magnetic field dynamics reveals an interesting distinction. In the sub-Alfvénic flow of the photosphere field lines can undergo four basic processes: they can erupt from below the photosphere, foot points can move, field lines can reconnect, and they can subduct to regions below the photosphere. In the solar wind there are only three processes: field lines can erupt from below the Alfvén critical point, they can move in the flow, and they can reconnect. Once released into the super-Alfvénic flow field line segments cannot subduct below the Alfvén radius. This leads to an interesting distinction between the rising and falling phases of the solar cycle. In the rising phase, new field lines can erupt from the photosphere and into the solar wind by passing magnetic loops across the Alfvén critical point. ICMEs accomplish this in a most dramatic manner. The PFSS model does it through rising field loops in a sequence of steady-state potential field predictions. Regardless of how they are contributed, once a field line passes over the Alfvén critical point it is unable to return to the sub-Alfvénic flow region. There are no means of subduction for interplanetary field lines in a super-Alfvénic flow. Therefore, during the falling phase of the solar cycle, and indeed for many field lines that are introduced during the rising phase as well, the only way to shed field lines is through magnetic reconnection below the Alfvén critical point. Simply put, rising loops can add to the IMF but falling loops cannot subtract from it. To the extent that the PFSS model does not contain reconnection, it might best be thought of as a prediction for the series of equilibria through which the solar field configuration passes during the declining phase of solar activity while the dynamics for that evolution is not contained within the model. The only means of achieving the low heliospheric field state of solar minimum is through reconnection of field lines and ejection with the solar wind flow. As the reconnection facilitates the reduction of the IMF it also turns open field lines into closed loops below the Alfvén critical point, which permits those loops to relax to the PFSS model prediction. Therefore, we contend that the observations described here constitute evidence of ongoing magnetic reconnection below the Alfvén critical point despite the lack of solar activity normally associated with ICMEs and rising magnetic loops. We further contend that the ability of the PFSS model to match a sequence of photospheric observations during the declining phase of the solar cycle is due, in part, to reconnection of open field lines that creates new photospheric loops that can then relax to the predictions of the force free model.

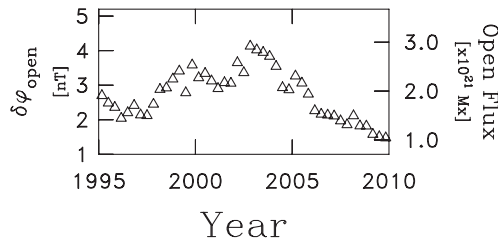


Figure 3. Average open flux (Figure 2(e)) recomputed for 4 month intervals. Note nearly steady decline of flux from 2002 onward in what might be characterized as a two-part process where reconnection associated with the last of the big CMEs influences the reconnection rate until the start of 2006 and thereafter a nearly steady, but more gradual decline that is associated with reconnection without the added input of new eruptions.

Note the behavior of $|B|$, B_R , and ϕ_{open} over the years 2005–2009. There is little or no toroidal flux ϕ_{toroid} of field lines associated with erupting loops. Solar activity is low. However, there is an ongoing decline in the IMF intensity and in the flux of field lines associated with the nominal Parker spiral direction. This suggests the loss of open field lines. To better illustrate the persistent decline, Figure 3 reproduces the average computed open flux as in Figure 2(e) using 4 month subsets of the data. The rate of decline in IMF intensity and open flux may not be constant, but it does continue in a nearly linear fashion from 2006 through the end of the analysis. As before, uncertainties are plotted in Figure 3, but are generally smaller than the symbols. It is tempting to interpret the decline of open flux for years 2003 onward as a two-phase rate with the greater rate occurring when a significant measure of solar activity is still present and then a lesser but steady rate during the quietest years (2006 onward). In the absence of disruptive activity (such as CMEs), there would seem to be an ongoing, if slower, rate of reconnection involving the open field lines that remain in association with the quiet Sun.

Figure 4 shows a representation of field line topologies for ICMEs or other emerging loop structures that draw out closed field lines (top), field line reconnection within the supersonic solar wind (middle), and field line reconnection below the Alfvén critical point or sonic point (bottom). The figure represents field lines close to the Sun where they remain largely radial. Focusing on the emerging closed field line geometry, the leading region contains the systematic contributions to ϕ_{toroid} and B_Y^P while the field lines extending toward the foot points agree with the Parker spiral direction. Each field line possesses a toward sector component, a strongly ϕ_{toroid} component, and an away sector component. If drawn out to 1 AU, the spiral structure of the fields leading back to their foot points would be evident, but the basic three-part structure is the same. Since every long-term average of the data is in essence a statistical sample of a volume average, we can compute the contribution to $\langle\phi_{\text{open}}\rangle$ made by the eruptive closed fields by measuring the $\langle B_Y^P \rangle$ component. For each field line with a B_Y^P contribution near the leading edge, there is a contribution to ϕ_{open} for each sector type provided by the fields leading back to the solar foot points.

We can adopt this to a familiar model (Owens et al. 2008): reconnection of field lines across current sheets below the Alfvén point produces a steady drain of IMF lines that are ejected from the heliosphere while the injection of closed field lines during the rising phase of the solar cycle replaces field lines previously lost to reconnection. This leads to a solar cycle effect wherein the rate at which new field lines are injected into the solar wind is greater than the expulsion rate of old field lines and the IMF intensity builds during the years leading up to solar

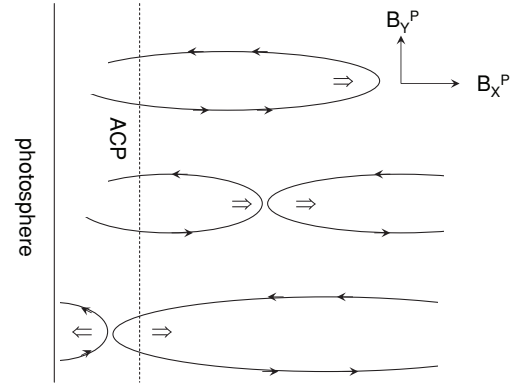


Figure 4. Representation of near-Sun field lines due to ICME eruption (top), magnetic field reconnection within the solar wind (middle), and field line reconnection below the Alfvén critical point (ACP) (bottom). Double arrows represent plasma flow.

Table 2
Declining Phase Time Derivatives

Stat	2007–2009 (nT yr ^{−1})	2006–2009 (nT yr ^{−1})	2005–2009 (nT yr ^{−1})
$\partial_t \langle B \rangle$	-0.28 ± 0.02	-0.36 ± 0.05	-0.49 ± 0.14
$\partial_t \langle B_R \rangle$	-0.26 ± 0.14	-0.20 ± 0.07	-0.29 ± 0.09
$\partial_t \langle \delta\phi_{\text{open}} \rangle$	-0.21 ± 0.09	-0.20 ± 0.04	-0.29 ± 0.09

maximum. The absence of injections, presumably due to the general reduction of CME eruptions or changing photospheric fields, halts the buildup of interplanetary field lines while the continuation of reconnection steadily depletes the heliospheric field and draws down the IMF intensity. Note the timing evident in Figure 2: the onset of ϕ_{toroid} predates solar maximum and marks the onset of the rise in $|B|$. Flux injection as represented by ϕ_{toroid} reaches a steady level in 1998 that lasts through 2003 while $|B|$ continues to increase. The average value of $\langle\delta\phi_{\text{toroid}}\rangle$ for these years is $(0.15 \pm 0.003) \times 10^3$ (nT km s^{−1}). At this time there is a steady injection of flux that exceeds the expulsion due to reconnection and the IMF intensity rises. Reconnection rates may increase at this time due to CME activity, but the injection of new field lines via CME eruption exceeds the removal of old field lines via reconnection. By year 2004 ϕ_{toroid} is decreasing, the rate of newly injected field lines is decreasing, and the expulsion of flux via reconnection again becomes dominant. By 2005 onward $\phi_{\text{toroid}} \simeq 0$ and all that remains is the steady removal of flux via magnetic reconnection. During the rising and falling phases of the solar cycle there is a propensity for most interplanetary field lines at 1 AU to conform to the nominal Parker spiral direction as injected flux moves outward through the heliosphere and “old” injected flux is represented by field lines following the Parker spiral in their return to their solar foot points.

Table 2 lists the fit rates of decrease for IMF parameters during the declining years of solar activity and into the current years of inactivity. We list fits for averages across the HCS only because it is evident from Figure 2 that toward and away sector polarities follow the same rates. Depending on the years chosen, the rate of decrease of $|B|$ varies from 0.28 to 0.49 nT yr^{−1}. The rate of decrease for B_R and $\delta\phi_{\text{open}}$ varies from 0.2 to 0.29 nT yr^{−1}. Since to good approximation $B_R \simeq \delta\phi_{\text{open}}$ owing to $\delta\phi_{\text{toroid}}$ being small and $B_R \simeq |B| \cos(45^\circ)$, these three rates are in good agreement.

It has been widely argued that field line reconnection is a common aspect of the early evolution of ICMEs. It should

Table 3
Rising Phase

Stat	1997–2003 (nT yr ^{−1})
$\partial_t \langle B \rangle$	0.27 ± 0.08
$\partial_t \langle B_R \rangle$	0.21 ± 0.04
$\partial_t \langle \delta\phi_{\text{open}} \rangle$	0.22 ± 0.05

probably be noted that it is likely to persist in the rising loops predicted by the PFSS model as well. This represents an additional rate of reconnection over and above what we see during solar minimum conditions. These reconnection events might best be viewed as moderating the injection of flux via erupting loops. If the underlying rate of magnetic field line removal were constant with the solar cycle, the rate of flux injection into the wind would be approximately twice the rate of flux removal via reconnection during the rising phase of the solar cycle in order for quantities such as $\langle |B| \rangle$ to appear as a symmetric function before and after solar maximum. The fit rates of flux increase during the rising phase of the solar cycle are contained in Table 3 and to a good degree they match the rate of decrease in the later years. However, flux injection can exceed this value if the reconnection rate increases commensurately. Therefore, it follows that the rate of flux injection must provide at least 0.63 to 0.76 nT yr^{−1} of IMF intensity at 1 AU. In our companion paper (Schwadron et al. 2010), we show that the observed rate of CME activity plus the observed properties of ICMEs satisfy this requirement.

It is desirable for closure to be able to interpret $\langle \phi_{\text{toroid}} \rangle$ in terms of a rate for field line injection during the rising phase of the solar cycle and to relate it to $\langle |B| \rangle$ and the rate of reconnection. To do this properly requires a detailed model of ICME topology and dynamics. As a step in this direction we can compare $\langle \phi_{\text{toroid}} \rangle$ with past estimates of flux injection by ICMEs. Those estimates are (Lynch et al. 2006; Schwadron et al. 2008) $(1. - 5.5) \times 10^{23}$ Mx yr^{−1}. During the active phase $\langle \phi_{\text{toroid}} \rangle \simeq 0.4 \times 10^{23}$ Mx yr^{−1}. Therefore, $\langle \phi_{\text{toroid}} \rangle$ represents only 10%–40% of total flux injection by ICMEs with the bulk of the remainder resembling open field lines. This contribution can be doubled if one considers field line closure in the north–south direction.

3. DISCUSSION

It is not uncommon to think of the IMF as a collection of open field lines into which CMEs erupt, adding flux, and then disconnecting to be swept out of the heliosphere. However, we observe the continued loss of flux during recent solar minimum years when there has been very little CME activity. This suggests the ongoing reconnection of open field lines or the reconnection of very old closed field lines injected months to years earlier. We contend that there is really no difference between these two interpretations and that what is important is that reconnection of apparently open field lines (field lines that closely follow the Parker spiral direction) continues without the injection of new flux via eruptive activity. Eruptive activity must be in the form of loops and can be part of CMEs or the PFSS model—both seek to introduce field loops into the supersonic flow of the solar wind.

We have adopted an interpretation wherein there exists a persistent reconnection of open field lines at current sheets below the Alfvén critical point that expels magnetic flux from interplanetary space even at times of solar minimum. This does not preclude additional or enhanced reconnection rates in

association with CME eruption when they occur. It only points to an ongoing reconnection in the absence of new field line eruptions. At the current rate it would take only 10–15 years starting in 2005 to deplete the IMF. We assert that this depletion would extend to high latitudes as the analysis of *Ulysses* data by Smith & Balogh (2008) and Connick et al. (2009) both show the depletion of open field lines in the same manner as is reported here. We do not predict such a depletion as the general reduction of open field lines would inhibit reconnection and lead to significant changes in the solar atmosphere, but such is the rate of the last few years.

We have not invoked any specific solar physics dynamics or magnetic reconnection theory. We have not adopted or dismissed the established association of open field lines with coronal holes (Wang 2009), although we certainly accept it as true. Detailed solar physics theory is necessary to predict the evolution of the heliospheric field if solar minimum were to continue. For instance, the observed reduction of photospheric magnetic field strength over the poles reduces the pressure within the corona and may enhance magnetic reconnection there and thereby facilitate ongoing reconnection during solar minimum (Y.-M. Wang & S. Antiochos 2010, private communication). Likewise, the physical separation of outward and inward polarity fields into the two polar hole regions must result in some added degree of difficulty in bringing together opposite polarity fields for the purpose of reconnection and, eventually, this must limit the rate of reconnection and greatly extend the time to IMF extinction.

Our analysis of “open” and “toroidal” fields has not used electron heat flux in an attempt to discern solar foot point connectivity. We have simply examined global averages of the IMF during the protracted solar minimum and drawn reasonable conclusions based on three basic physics assumptions: rising loops of magnetic field (originating either from the eruptive processes of CMEs or the implied process of PFSS models) adds new flux into the solar wind, magnetic reconnection removes flux, and no other dynamics can change the global average IMF intensity within the solar wind. These things seem agreed upon by the community and are a direct result of supersonic and super-Alfvénic flow physics. Others have performed analyses of the open and closed field lines of individual ICMEs, estimated their volumes, and integrated their magnetic flux, and we have shown basic agreement with their results. Based on these reasonable assumptions, the rate of field line removal due to reconnection is obtained and the conclusions regarding protracted solar minima become unavoidable.

4. SUMMARY

We have examined magnetic field data from 1995 through 2009 that includes the recent protracted solar minimum using data from the Omni data set at 1 AU. We have seen that the IMF intensity drops consistently during the solar minimum years. We suggest that the only explanation for this observation is the ongoing reconnection of nominally open field lines and argue that field line reduction results because there are very few eruptions of new field lines to replace the field lines lost via magnetic reconnection. One must question how long open field line reconnection can continue as the dipolar nature of the Sun’s field at solar minimum segregates field line polarities into the two polar regions. Significant changes in solar atmospheric conditions (reduced source height, for instance) are needed or the reconnection processes inferred here would become depleted.

The authors thank the National Space Science Data Center for providing data used in this study. We thank the SIDC for sunspot data used in this study. D.E.C. and C.W.S. are funded by Caltech subcontract 44A-1062037 to the University of New Hampshire in support of the ACE/MAG instrument. N.A.S. is funded by the NASA EMMREM project. The authors thank S. Antiochos, N. Crooker, L. A. Fisk, and Y.-M. Wang for helpful and stimulating conversations during the performance of this work.

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